IS THE UPSILON A BOUND STATE OF EXOTIC QUARKS?*

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ABSTRACT

To explain the T-T´ mass splitting of the recently discovered T resonances, we interpret them as bound states of a quark and an anti-quark which are not members of the fundamental ($\underline{3}$) representation of color SU($\underline{3}$). A quark in the $\underline{8}$ (or maybe $\underline{6}$) representation is consistent with the data. We discuss some of its properties and the phenomenological consequences that follow from our suggestion.

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It is widely accepted that the newly discovered upsilon resonance[1]
T (9.4) is a bound state (b$\bar{\text{b}}$) of a fifth quark b and its antiquark.
However, the experimentally observed splitting[2] of the T and T' is too
big to be explained by the same (essentially) linear potential that has
been applied so successfully to the phenomenology of the ψ spectroscopy[3]
(at least in the non-relativistic approximation). To be specific, the
potential used by Eichten et al.[4] gives a splitting of 0.4 GeV instead
of the observed $M_{T'}-M_{T} \simeq 0.6$ GeV.

To explain the observed splitting, other non-relativistic potential
models have been suggested.[5,6] For example, a logarithmic potential[5]
seems to be consistent with both the ψ and T spectroscopies in the non-
relativistic limit. However, such potential models provide little con-
nection to other aspects of hadronic phenomena.

On the other hand, recent theoretical investigations on quark
confinement, linear Regge trajectories for light hadrons, ψ spectroscopy
and other hadronic properties strongly indicate a string-(or vortex-)
like picture for hadrons. A linear potential arises non-relativistical-
ly in any string-like model. Hence, before abandoning such an intuiti-
vely simple picture, it is important to find an explanation for the
large T-T$'$ mass splitting within a simple string model.

One obvious possibility is that T and T$'$ are bound states of two
different types of quarks. In particular, using either a simple linear
potential[7] or the modified one of Ref. 4, the first radially excited
state of the ground state T(10.0) occurs at roughly 10.4 GeV, precisely
where some structure[2], namely T$''$(10.4), has been observed. The real T$'$
is then presumably buried between the T(9.4) and T (10.0).

Another possible explanation within the string picture, suggested by Giles and Tye[8], is that the T (and T´) is a bound state of an exotic quark-antiquark pair, i.e. quarks which are not in the fundamental representation $\underline{3}$ of color SU(3).[9,10] In this Letter we would like to emphasize the likelihood of such an exotic quark. We elaborate on the dynamical reasoning behind this possibility and discuss some of its fascinating phenomenological consequences. Experimentalists studying "upsilon" physics should bear in mind this intriguing possibility.

Since hadron physics is still poorly understood, our dynamical reasoning must necessarily be model dependent. We shall assume exact color confinement; for the sake of clarity and definiteness we shall discuss within the framework of the quark-confining string (QCS) model[11], which is assumed here to be a phenomenological model[12,13] of quantum chromodynamics (QCD). Our attitude and philosophy is very similar to that of Eichten et al.[4] Hence it should be obvious that the validity of our argument is more general; for example, we believe it is equally applicable to lattice gauge theories[14].

In the QCS quark confinement arises from the confinement of the color electric flux along a string. The quark-gluon coupling g (with dimension of mass) is related to the asymptotic Regge slope $\alpha´$

$$\alpha´^{-1} = 2\pi C \frac{g^2}{2} \equiv 2\pi k \tag{1}$$

where C is the color charge-squared Casimir operator. For quarks in the fundamental representation of color SU(N), $C = (N^2-1)/2N$. Gauge invariance requires g to be universal for all quarks.

In Table 1, $\alpha´$ for the quarks are given. Some explanations are

needed. Since the QCS has proper chiral symmetry properties[15], the pion mass can be related to the quark masses by $m_\pi^2 = \frac{1}{\sqrt{\alpha'}}(m_u + m_d)$. Using the current quark mass ratios obtained from current algebra[16], we arrive at the masses of the light quarks shown in Table 1. We note that the quark masses obtained here are very close to those expected of the current quark masses[16]. The Regge slope and the mass for the charmed quark are extracted from ψ spectroscopy[17]. Naively, the Regge slope obtained by interpolating the ψ and χ states is roughly 0.4 GeV^{-2}, instead of 0.8 GeV^{-2} as shown in Table 1. However, the difference is entirely due to the effects of massive quarks[18]. The Regge slope will approach its asymptotic value α' as $\frac{m_c}{M} \to 0$, where M is the mass of a pure rotationally excited state (i.e. no radial or vibrational modes).

When the QCS is applied to the Υ spectroscopy, it is found[8] that α' acquires a much smaller value $\alpha' \approx 0.4$ GeV^{-2} or $k \sim 0.41$ GeV^2. Such a large value of k can be accounted for by putting the new quark Q in the **8** (a zero-triality) representation of color SU(3): $k(\underline{8}) \approx \frac{9}{4}(0.2)$ GeV^2. Due to the uncertainties inherent in our estimates, we cannot rule out the **6** (a non-zero triality) representation: $k(\underline{6}) \approx \frac{5}{2}(0.2)$ GeV^2. The strength of the linear potential is too strong for higher representations; for instance $k(10) \approx \frac{9}{2}(0.2)$ GeV^2. Properties of both the octet and sextet quarks are included in Table 2. We should mention that the shifts of the energy levels of the Υ spectroscopy due to the inclusions of a small coulomb term in the potential is negligible.

Let us now concentrate on the octet quark Q. The lightest color singlet hadrons containing Q are fermions $(Qq_1\bar{q}_2)$ and antifermions $(\bar{Q}q_2\bar{q}_1)$ where q_i is an old quark (u,d,s,c). The lightest boson is

(Qqqq). In fact, for every (old) meson and baryon state observed, there
is a corresponding new state by attaching a Q or $\bar{Q}$ to it. The existence
of Q obviously presents a very rich spectroscopy. In passing we should
also mention the possible existence of hadrons composed of Q and gluon.

As long as the strong gauge group and the weak gauge group commute,
the bare Q quark is stable under color SU(3) and the weak and electro-
magnetic interactions (e.g. the SU(2) × U(1) model of Weinberg and
Salam[19]). The Q quark will thus play no role in the weak interaction
phenomenology involving (Qq$\bar{q}$) or (Qqqq). However, it is likely that Q
can decay (albeit slowly) into color gluons, standard quarks, and/or
leptons in an unified theory of strong, weak and electromagnetic inter-
actions[20]. In case it is stable or metastable, hadrons formed out of it
will exhibit many remarkable features discussed by Cahn.[21] In the QCS
the ground state meson (Qqqq) cannot decay into (Qq$\bar{q}$) and (qqq) due to
lack of phase space. Hence we expect the lowest-mass bosonic states as
well as the lowest-mass fermionic states to be stable or metastable. If
the electric charge (e_Q) of Q is fractional (integral) then all hadrons
consisting of one Q quark also have fractional (integral)
charges. For fractional e_Q it will be difficult to distinguish
the signal for such hadrons from free quarks. Since the present
weak interaction phenomenology does not require a new quark flavor
at this mass, Q can have any of the known flavors or any combination
of them. It may also have a new flavor. Its baryon number is not
determined.

In the e^+e^- annihilation channel, the continuum threshold (c.t) of
Q is determined by the (Qu$\bar{u}$) ($\bar{Q}$u$\bar{u}$) pair. A rough estimate gives m(Qu$\bar{u}$)∿

5.8 ± 0.5 GeV. With the continuum threshold at around 11.6 GeV, there are many radially excited and vibrational states below the threshold in the e^+e^- channel. A very rich array of radiative transitions is expected. This is particularly prominent in the QCD framework, since the three gluon decay mode is completely suppressed. Let us elaborate on this point.

Assuming QCD it is straightforward to calculate the decay modes of $T(Q\bar{Q})$. Denoting the energy of the system by M, the wavefunction at the origin by $\psi(0)$, we have, at resonance $(M^2 \sim 4m_Q^2)$ the three-gluon, one-photon-plus-two-gluon and the muon-pair decay widths respectively

$$\Gamma(3g) = G_{3g}\Gamma(3\gamma) = G_{3g} \frac{16}{9} (\pi^2-9) \frac{4\alpha_c^2}{M^2} |\psi(0)|^2 \qquad (2a)$$

$$\Gamma(2g+\gamma) = G_{2g+\gamma} \frac{\alpha}{\alpha_c} e_Q^2 \Gamma(3\gamma) \qquad (2b)$$

$$\Gamma(\mu^+\mu^-) = G_\gamma e_Q^2 \frac{16\pi}{3} \frac{\alpha^2}{M^2} |\psi(0)|^2 \qquad (2c)$$

where α is the fine structure constant and α_c is the color coupling constant. The coefficients G are given in Table 2 which also summarizes some interesting properties of Q. We note the remarkable feature that the $\underline{T}(Q\bar{Q})$ cannot decay into three gluons if Q is in the $\underline{8}$ representation. However it can still decay into hadrons via the intermediary of a photon and two gluons whose momenta are coplanar. In this respect it is helpful to recall that the angular distribution for this decay[22] goes as $(3-\cos^2\theta^*)$ where θ^* is the center-of-mass angle for the normal of the decay plane relative to the e^+e^- (which produces the T) beam direction. The distribution of hard photons[22] $(\frac{2E_\gamma}{M_T} \to 1)$ behaves like $\left(1+\cos^2\theta_\gamma\right)$ with θ_γ being the angle between the photon and the e^+e^- direction. The angular distribution on the decay plane of the photon and the two hadronic jets

resulting from the two gluon fragmentation is still the same as that given for the three gluon case.[13] These distributions would provide a very clean test for QCD.

We can also make an educated guess at the decay widths of T and T´. These widths have large uncertainties and are given only for illustrative purposes. Following Eichten and Gottfried[23] we obtain for the octet quark $\Gamma(T \to \text{all}) \simeq 179 e_Q^2$ keV, $\Gamma(T´ \to \text{all}) \simeq 176 e_Q^2$ keV $+ \Gamma´$, and the muon-pair branching ratios $B(T \to \mu^+ \mu^-) \simeq \frac{16.3}{179}$ and $B(T´ \to \mu^+ \mu^-) \simeq 10 e_Q^2 / (176 e_Q^2 + \Gamma´)$ where we have used $\alpha_c(m_T) \simeq 0.15$ and have denoted the $T´ \to T\pi\pi$ decay width by $\Gamma´$. Let R_p be the primordial hadronic production of T´ to T ratio. The ratio of the observed $\mu^+ \mu^-$ signals at Fermilab is then given by[1,2]

$$R_\mu = \frac{R_p}{1+R_p B(T´ \to T+X)} \frac{B(T´ \to \mu^+ \mu^-)}{B(T \to \mu^+ \mu^-)} \simeq 0.4 \quad . \tag{3}$$

Assuming $R_p \leq 1$ such that $R_p / \left[1+R_p B(T´ \to T+X) \right] < 1$ gives $B(T´ \to \mu^+ \mu^-)/B(T \to \mu^+ \mu^-)$ >0.4. Following Ref. 23 and 24 we estimate that $\Gamma´ \sim 48$ keV. The inequality then becomes

$$64 e_Q^2 > 31 \quad . \tag{4}$$

Hence it is possible that $e_Q^2 = 1$,[25] a value we prefer since all new hadrons would then have integral charges. This would result in a dramatic rise in R in $e^+ e^-$ annihilation.

So far we have discussed the octet representation. For the 6 quark, the lightest hadron formed out of it is $(Q\bar{q}\bar{q})$, again a fermion.[10] For all new hadrons to have integral charges we must assign $e_Q = \frac{1}{3} \pm$ integer. Some of the properties of the sextet quark are summarized in Table 2.

In conclusion we have suggested that the upsilon resonances are

bound states of color octet (or perhaps sextet) quarks. The phenomeno-logical consequences we have outlined in this paper can be cleanly tested in the e^+e^- annihilation machines in the near future.

FOOTNOTES AND REFERENCES

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2. W. R. Innes et al., Phys. Rev. Lett. 39, 1240, 1640(E) (1977).

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9. The possible existence of quarks in representations other than the 3 has been suggested by many theorists (see Ref. 10). Inevitably, the argument for the existence of such exotic quarks ranges from a "why not?" to pure theoretical speculations. We believe ours is the first argument, albeit model dependent, based on T phenomenology.

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12. For more discussion on this point of view, see Sec. 5 of the second paper in Ref. 11. For another point of view see Ref. 13. We note that the argument to be given below for the evidence of T as a bound state of exotic quarks does not depend on QCD.

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17. R. C. Giles and S. -H. H. Tye, Phys. Rev. Lett. 37, 1175 (1976); Phys. Rev. D16, 1079 (1977).

18. See A. Chodos and C. B. Thorn, Nucl. Phys. 72B, 509 (1974), in particular Eqs. (2.7)-(2.9).

19. S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in Elementary Particle Physics, ed. by M. Svartholm (Almquist and Wiksells, Stockholm, 1968), p. 367.

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25. Assuming $e_Q = \pm 1$ and that the Q is in the $\underline{8}$ representation, we should expect neutral, charged ± 1, ± 2 fermionic hadrons with mass $\gtrsim 5.8 \pm 0.5$ GeV and neutral, charged ± 1, ± 2, ± 3 bosonic hadrons with mass $\gtrsim 6.0 \pm 0.5$ GeV. We also expect a production cross-section of the order of 10^{-36} to 10^{-34} cm^2/GeV. This will be a crucial test of the existence of exotic quarks.

26. H. D. Politzer, Phys. Rev. 14C, 130 (1974).

TABLE CAPTIONS

1. For all the old ($\underline{3}$) quarks which have masses ranging from 7 MeV to 1.15 GeV the asymptotic Regge slope $\alpha' \simeq 0.8$–0.9 GeV^{-2} (corresponding to k $\simeq 0.2$ GeV^2). But α' for the new quark Q has only half that value.

2. Table showing the color charge-squared Casimir operator C, the continuum threshold (c.t.), the S states and the vibrational states in GeV below c.t. in the e^+e^- channel (relativistic corrections < 100 MeV to the energy levels have not been included), the increase in the hadronic to μ-pair ratio R in e^+e^- annihilation, the contribution to C_2 of the β-function (see Ref. 26 for notations) and the decay coefficients G corresponding to the three color representations for the new quark.

TABLE 1

quark	mass m	α'
u (up)	7 MeV	0.9
d (down)	12 MeV	0.9
s (strange)	0.22 GeV	0.8-0.9
c (charm)	1.15 GeV	0.8
Q	4.3 GeV	0.4

TABLE 2

Representation	$\underline{3}$	$\underline{6}$	$\underline{8}$
C	$\dfrac{4}{3}$	$\dfrac{10}{3}$	$\dfrac{9}{3}$
c.t. (in GeV)	10.8	11.6	
S states	9.4,10.0,10.5	9.4,10.0,10.5,10.9,11.3	
Vibrational states	10.6	10.6,11.0,11.2,11.3,11.5	
ΔR	$3e_Q^2$	$6e_Q^2$	$8e_Q^2$
ΔC_2	1/2	5/2	6/2
G_γ	3	6	8
G_{3g}	5/18	$\dfrac{5}{18} \times \dfrac{49}{2}$	0
$G_{2g+\gamma}$	2	25	27